

UCRL-90859
Preprint

NONDESTRUCTIVE DETECTION OF RAYLEIGH
WAVE DISPERSION IN BERYLLIUM

R. D. Weglein
J. E. Hanafee

This paper was prepared for submittal to
Applied Physics Letters

June 1, 1984

Lawrence
Livermore
National
Laboratory

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

NONDESTRUCTIVE DETECTION OF RAYLEIGH
WAVE DISPERSION IN BERYLLIUM*

R. D. Weglein

6317 Drexel Avenue

Los Angeles, CA 90048

J. E. Hanafee

Lawrence Livermore National Laboratory

Livermore, CA 94550

ABSTRACT

The presence of machining damage in beryllium may be determined nondestructively in the acoustic microscope via the acoustic material signature (AMS). Rayleigh wave dispersion is attributed to substantial modification of the macroelastic properties in the surface region due to the machining process. Comparison of acoustic material signatures at 35 MHz obtained from chemically etched (undamaged) and machining-damaged (MD) specimens show substantial (3%) Rayleigh velocity reduction in the latter. Damage variation with depth may be ascertained via AMS measurements over a wide frequency range.

*This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

Machining damage may be determined nondestructively in the acoustic microscope via the acoustic material signature (AMS) technique.¹ This hypothesis is based on the premise that the elastic properties of the damaged layer are altered by the machining process. If modification of the surface region actually occurs, Rayleigh wave dispersion results² in the surface region of the machined beryllium surface. Before machining, the half space was uniform where the Rayleigh velocity is not a function of frequency.

Substantial improvement in the mechanical properties of beryllium over the past decade has led to an expansion of its applications with greater confidence. With high specific strength and specific modulus, beryllium is an ideal material for guidance and optical systems as well as for structural components in satellite and aerospace structures. Isotropic ultimate strength greater than 550 MPa (80 000 psi) yield strength in excess of 350 MPa (50 000 psi) and more than 3 percent elongation have been achieved. These properties can be obtained reproducibly for powder-origin beryllium.

In machining beryllium a thin layer of disturbed material may be created in the first approximately 100 μm of material immediately below the machined surface.^{3,4} The nature of the machining-damaged (MD) layer varies somewhat, but it is composed of three fundamental phenomena. First, and the most recognized, is twinning of the crystallographic structure. Second, there is a cold worked structure with greatly increased dislocation density and point defects. Third, there is most likely a strong crystallographic texture of the polycrystalline beryllium in this MD layer.³ This MD layer has important practical consequences as it seriously degrades the mechanical strength of beryllium, decreasing the strength as much as 20 to 30 percent, and elongations can drop from well over 3 percent to less than 1 percent.³ In situations requiring great dimensional stability such as optical and guidance

systems, it is conceivable that the MD layer may be disruptive to performance under some conditions. Recently we have found that acoustic microscopy can detect machining damage in beryllium. In what follows, we describe the experiment and discuss the results.

A single specimen approximately 2-in. square and 1/2-in. thick was machined and carefully etched to remove all machining damage. The specimen was cut in half and one part was subjected to a rough machining procedure. Small microstructural specimens were taken from each half and the remaining portion was subjected to the acoustic microscopy. The specimens were cross sectioned perpendicular to the surface being studied so that the microstructure at and below the surface could be observed (Fig. 1). In Fig. 1(a), the as-etched specimen is shown and the absence of machining damage is apparent. The MD specimen is shown in Fig. 1(b). The damage consists of cold-worked grains within about 25 μm of the surface and twinning extending to about 60 μm . This is a moderate degree of damage. Considerably more microstructural damage can be obtained.

A relatively large number of Rayleigh velocity measurements were made on both the MD and etched (undamaged) surfaces of the beryllium specimens, via the AMS technique at a frequency f of 35 MHz. The acoustic microscope⁵ used for this experiment is digitally controlled and automatically records the AMS in graphic form as the specimen is translated axially toward the lens. The AMS arises from interference of two active portions of the highly convergent acoustic beam, generally employed in this type of instrument. The two portions consist of a pencil beam, normally incident on the specimen along the lens axis, and of a conical-shell beam, incident at the critical angle to excite leaky Rayleigh waves in the specimen. These two components recombine in the piezoelectric transducer where they are summed vectorially to produce

the AMS with period Δz_N . The instrument computes the Rayleigh velocity v_R (Ref. 6 from Eq. (1))

$$v_R = v_1 / (1 - (1 - v_1 / 2f \times \Delta z_N)^2)^{1/2} , \quad (1)$$

where v_1 is the velocity of compressional waves in water.

Examples of typical AMS curves on the MD and etched beryllium surfaces are shown in Fig. 2. The AMS period and hence the Rayleigh velocity v_R differ on the two surfaces. The results of a number of these measurements are summarized in Table 1. Test 1 lists the results from Fig. 2. Tests 2 through 5 each list the mean velocity taken from three or four measurements at different locations on the MD and undamaged (etched) surfaces. In all cases the Rayleigh velocity on the MD surface is reduced by between 2.3 and 3.2 percent as compared to the original surface.

Table 1. Measured Rayleigh velocities.

| Test number | Frequency (MHz) | Lens type ^a | Rayleigh velocity (mm/ μ s) | | v/v _R (%) |
|-------------|-----------------|------------------------|---------------------------------|-------------------|----------------------|
| | | | Etched | Machining damaged | |
| 1 | 35 | S | 8.070 | 7.823 | -3.06 |
| 2 | 35 | S | 8.070 | 7.81 | -3.22 |
| 3 | 35 | S | 8.070 | 7.82 | -3.10 |
| 4 | 35 | C | 7.82 | 7.64 | -2.30 |
| 5 | 35 | C | 7.82 | 7.61 | -2.69 |

^a S is spherical and C is cylindrical.

Table 1 further shows that measurements were also made with a cylindrical lens incorporating a transducer identical to the design used in the spherical lens. A cylindrical lens excites Rayleigh waves solely along one direction, on the specimen, normal to the cylinder axis.⁷ On the other hand, a spherical lens excites a radially propagating Rayleigh wave pattern that is centered on the converging beam axis. The cylindrical lens was used here, because it was thought that the machining operation might produce some detectable surface anisotropy oriented relative to the direction of the machining tool travel. This did not materialize in these early experiments.

Finally, longitudinal and shear velocity measurements were performed on both specimens (with and without machining damage) at 5, 10, and 20 MHz. This was done to verify the elastic bulk properties of the two specimens, and compare the bulk-derived Rayleigh velocity⁸ with values obtained from the AMS. The beryllium specimen in these bulk velocity measurements was between 5 and 19 wavelengths thick, thus reducing to a negligible value any surface-related effects due to the machining damage depth (approximately 25 μm or 0.04 wavelength thick at 20 MHz). Table 2 lists these results that

Table 2. Bulk velocity measurements on a beryllium specimen.

| Velocity | Velocity (mm/ μs) | | % change |
|--------------|-------------------------------|-------------------|----------|
| | Etched | Machining damaged | |
| Longitudinal | 13.16 | 13.12 | -0.3 |
| Shear | 9.05 | 9.07 | +0.2 |
| Rayleigh | 7.92 | 7.92 | 0.0 |

show, (1) the identical bulk properties (within experimental error) of the two specimens, and (2) identical bulk derived Rayleigh velocities of the two specimens that agree within 1 percent with the AMS results from the spherical lens.

From the results presented in Fig. 2 and Table 1, the presence of machining-induced damage in the beryllium surface can be nondestructively detected with good confidence. This is in spite of the fact that the machining damage is moderate and that the metallurgically observed damage penetrated to a shallow $0.1\lambda_R$ ($25\ \mu\text{m}$) into the beryllium surface. The actual effective penetration depth is not known and remains to be investigated via depth profiling with the AMS technique at higher RF frequencies than were used in the present experiment. The highest frequency at which AMS curves may be obtained in beryllium is currently being investigated. The magnitude of the rapidly increasing acoustic attenuation with frequency in hot-pressed beryllium due to grain scattering and inherent loss mechanisms is presently unknown. Thus, high frequency investigation may well be limited to below 100 MHz, the present upper frequency limit of the acoustic microscope instrumentation.⁵

Rayleigh dispersion due to the damaged layer cannot at present be predicted because the layer is not abrupt and because the gradual transition from layer to undamaged microstructure entails presently unknown density and elasticity variations with depth as well as possibly altered acoustic attenuation. Experiments to develop parameter variation along these lines are in the planning stage. A theoretical treatment of Rayleigh dispersion that is parameter dependent will follow the direction pursued earlier in seismology where sound propagation along segmented layers has been studied.⁹

It is conjectured that the experimentally measured Rayleigh velocity dispersion might produce anomalous results. Certain machining processes leave a thin surface region of the beryllium specimen in a crystalline state consisting of hexagonal crystals with their basal plane parallel to the surface. In such a layer the Rayleigh velocity might be substantially lower than the measurements of Table 1 indicate, because the corresponding bulk velocities are somewhat lower.¹⁰ The resulting dispersion might, therefore, be influenced by this anisotropic cover layer as well as by the underlying damaged region of as yet unknown random orientation and macroelastic state.

Evidence of machining-induced anisotropy was not observed with the cylindrically shaped beam. This was not totally unexpected in view of the moderate machining damage inflicted in this particular specimen. If velocity anisotropy was indeed present, its detection would require substantially increased velocity resolution than is discernible (>1%) at the present state of development of this acoustic microscope. Further, Rayleigh velocity anisotropy of single-crystal beryllium itself can be quite small, judging from the known variation of the longitudinal and shear velocities with direction that range between 7 and 10 percent, respectively.

In conclusion, Rayleigh wave dispersion due to machining damage in beryllium has been observed for the first time. The dispersion is attributed to substantial modification of the macroelastic properties in the surface region due to the machining process. Dispersion was not detected in the etched (undamaged) material surface. Damage variation with depth is deemed possible via AMS measurements over a wide frequency range. Because the diagnostic technique is completely nondestructive and rapidly executed, it may become an important tool in the development of a high-quality, economic

fabrication technique for beryllium-based structural components in the satellite and aerospace industries.

The authors acknowledge the assistance of LLNL's S.E. Benson who obtained the numerous AMS curves and bulk measurements. The authors also appreciate critical review of the manuscript by B. D. Cook, visiting professor from the University of Houston, Texas.

REFERENCES

- ¹R. D. Weglein, Appl. Phys. Lett. 34, 179 (1979).
- ²E. G. Lean, Appl. Phys. Lett. 19, 356 (1971).
- ³J. E. Hanafee, J. Appl. Metalworking 1, 41 (1980).
- ⁴S. Beitscher, Beryllium Science and Technology (Plenum, New York), (1979),
p. 197.
- ⁵R. D. Weglein, R. F. Wilson, and B. W. Maxfield, Proc. Ultrasonics
International (Butterworth Scientific Ltd. Publ.) (1983), p. 270.
- ⁶W. Parmon and H. L. Bertoni, Electron. Lett. 15, 684 (1979).
- ⁷J. Kushibiki, A. Ohkubo, and M. Chubachi, Proc. 1981 Ultrasonic Symp.,
IEEE, (IEEE, N.Y.), Cat. No. 81CH1689-9, p. 552.
- ⁸B. A. Auld, Acoustic Fields and Waves (John Wiley & Sons, N.Y., 1964),
Vol. II, Chap. 10c.
- ⁹L. M. Brekhovskikh, Waves in Layered Media (Academic Press, 1980),
Chap. III.
- ¹⁰J. F. Smith and C. L. Arbogast, J. Appl. Phys. 31, 99 (1960).

Captions for UCRL-90859

(Weglein-Hanafee paper for Applied Physics Letters)

Figure 1. Metallurgical cross section of beryllium surfaces: (a) etched surface (200×), (b) machining-damaged surface (200×). The gray surface layer in both photomicrographs is a protective layer.

Figure 2. Acoustic material signatures on etched (undamaged) and machining damaged surfaces of beryllium.

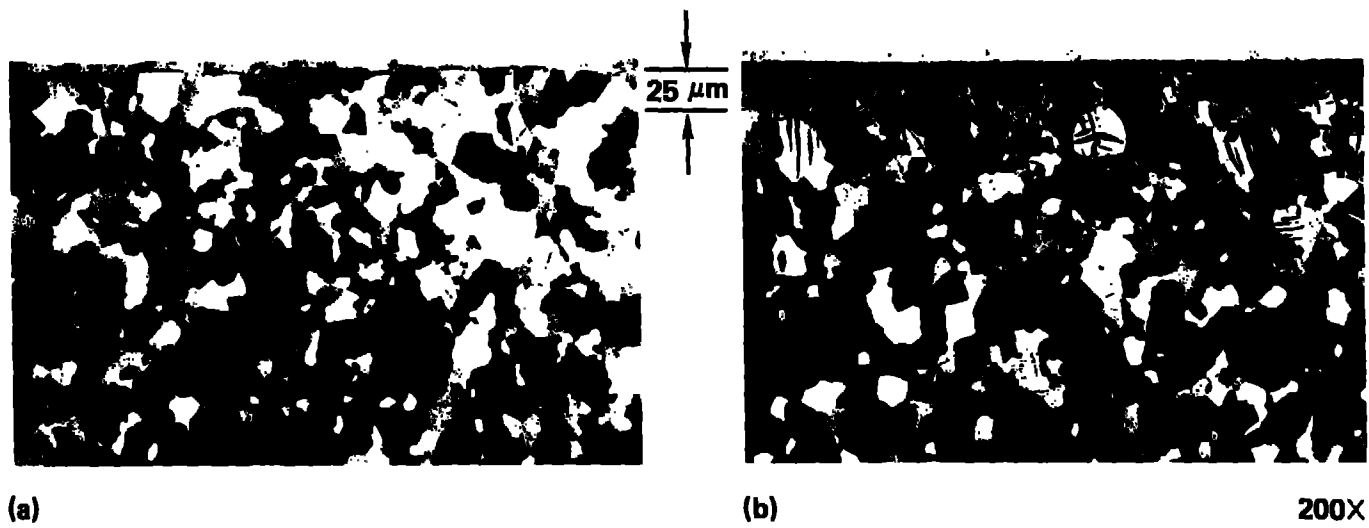


FIG. 1 - Weglein-Hanabee

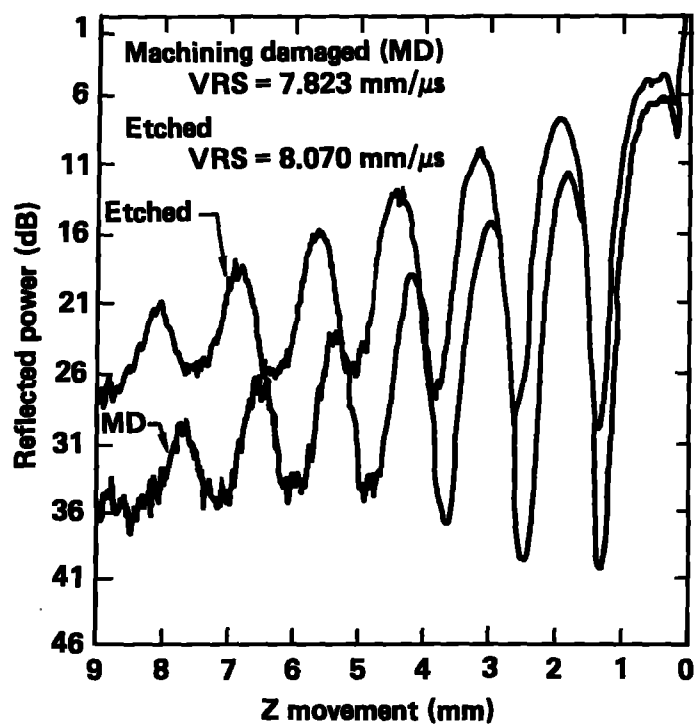


FIG. 2 - Weglein-Hanafee